AGU FALL MEETING

New Orleans 11-15 Dec. 2017

Modeling of Thermospheric Neutral Density Variations in Response to Geomagnetic Forcing using GRACE Accelerometer Data

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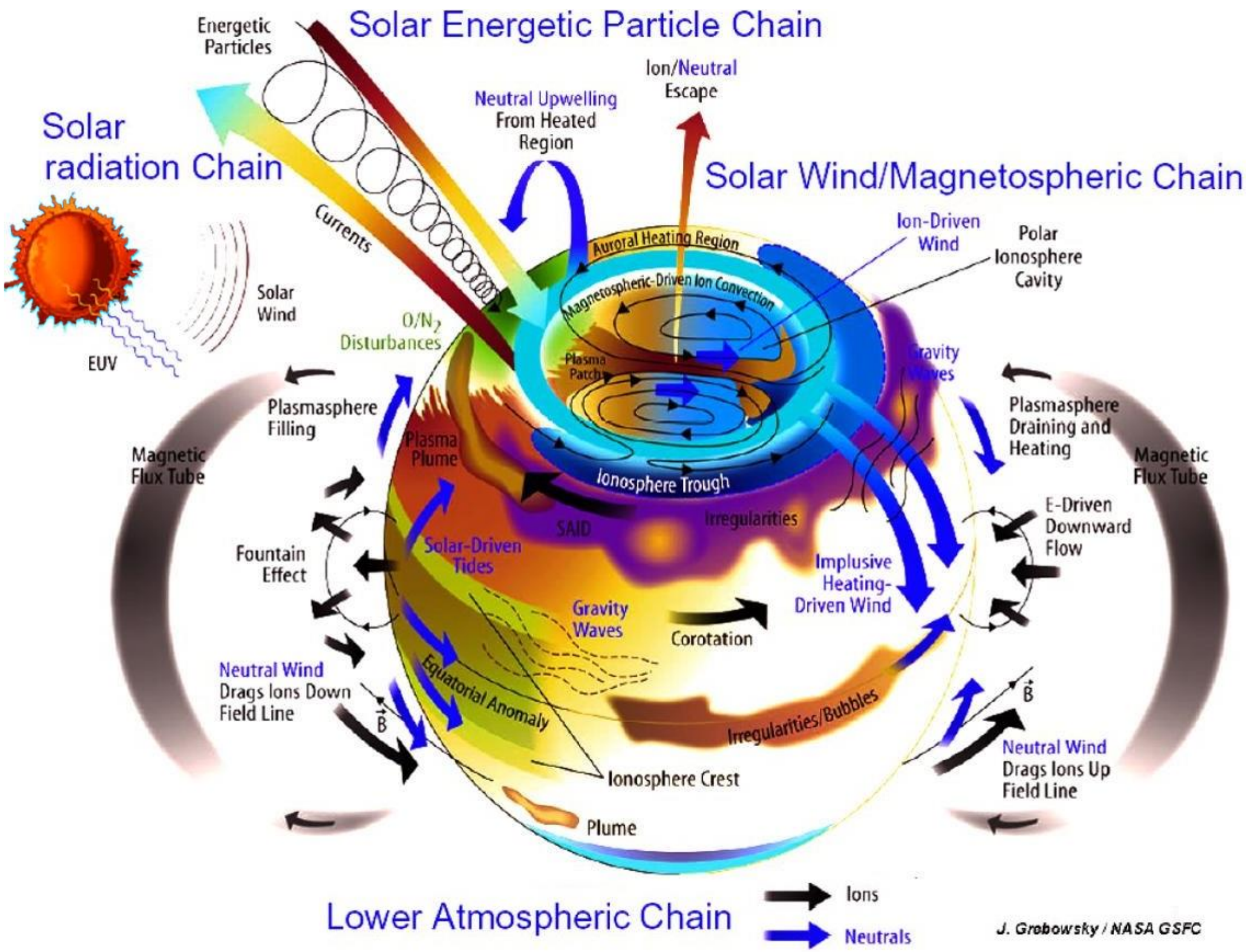
Content

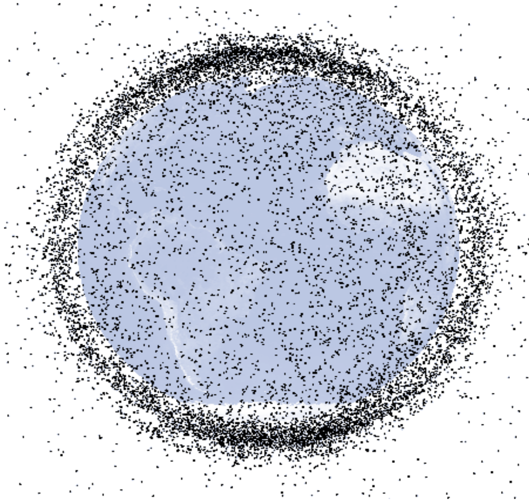
1. Introduction & Background

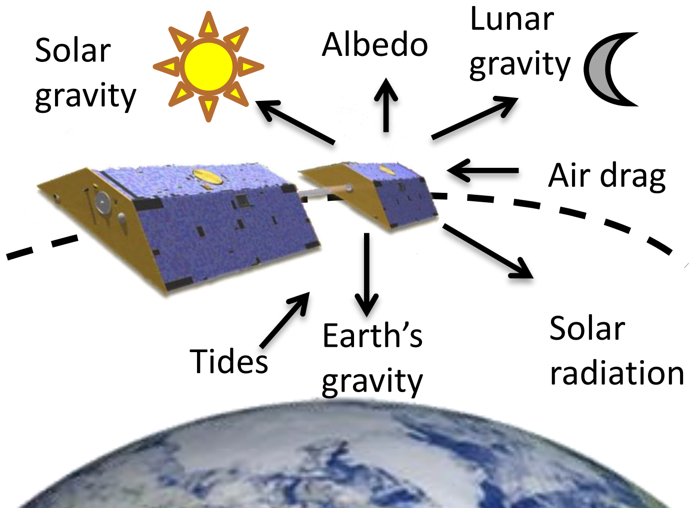
Upper atmosphere processes are not well understood and the current geophysical models are unable to predict the variability as accurately and efficiently required.

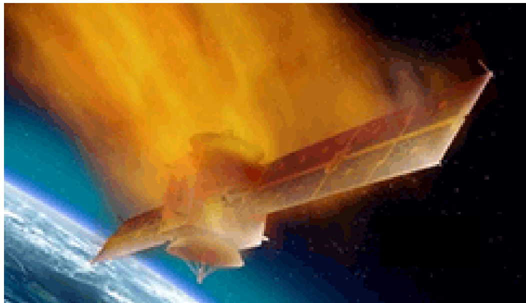


1. Introduction & Background

Half of the world's active satellites (~1000) and about 20,000 inactive debris operate in LEO, where atmospheric drag produce orbital decay and perturbations.







2. Methods & Data processing

Drag force for density retrieval

- Drag-force formula:

$$F_D = ma_D = \frac{1}{2} CA\rho v_r^2$$

C Drag coefficient (Cook, 1965; Metha et. al, 2013)
A Cross-sectional area
ρ Atmospheric density
v_r Relative velocity of the atmosphere
m Satellite mass
a_D Aerodynamic acceleration

- Normalization to common altitude :

$$\rho(475km) = \rho_{obs}(h) \frac{\rho_{mod}(475km)}{\rho_{mod}(h)}$$

*Bruinsma et al. (2006)

2. Methods & Data processing

Aerodynamic acceleration

Radiation-pressure removal:

Solar radiation

$$a_{sr} = \sum_{i=1}^{n_p} -\frac{E_{sr} A_i \hat{n}_i \hat{s}_{Sun}^{sat}}{mc}\left[2\left(\frac{c_{rd,i}}{3} + c_{rs,i}\hat{n}_i \hat{s}_{Sun}^{sat}\right)\hat{n}_i + \left(1 - c_{rs,i}\right)\hat{s}_{Sun}^{sat}\right]$$

Earth albedo

$$a_{ea} = \sum_{i=1}^{n_p}\sum_{j=1}^{grid} -\frac{E_{ea,j} A_i \hat{n}_i \hat{s}_j^{sat}}{mc}\left[2\left(\frac{c_{rd,i}}{3} + c_{rs,i}\hat{n}_i \hat{s}_j^{sat}\right)\hat{n}_i + \left(1 - c_{rs,i}\right)\hat{s}_j^{sat}\right]$$

$$E_{ea,j} = \mathrm{E}_{\mathrm{ea}}^{\mathrm{R}} + \mathrm{E}_{\mathrm{ea}}^{\mathrm{IR}}$$

$$\mathrm{E}_{\mathrm{ea},j}^{\mathrm{R}} = f_j v_j E_{sr}\frac{A_j\left(\hat{n}_j \hat{s}_j^{Sun}\right)\left(\hat{n}_j \hat{s}_j^{sat}\right)\sigma_{\mathrm{TOMS}}}{\pi\left|\hat{s}_j^{sat}\right|^2}$$

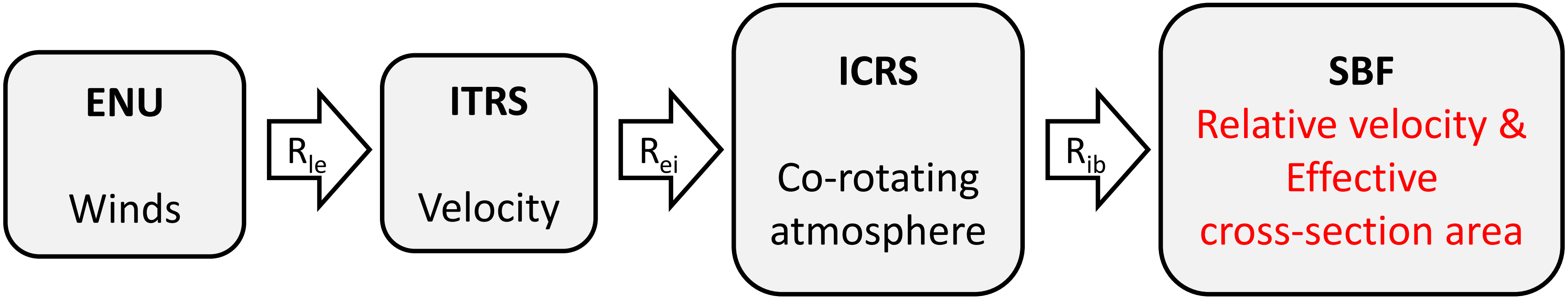
$$\mathrm{E}_{\mathrm{ea},j}^{\mathrm{IR}} = f_j 239\left(\frac{1\mathrm{AU}}{s_{Sun}^{j}}\right)^2 e_{IR,j}\frac{A_j \hat{n}_j \hat{s}_j^{sat}}{\pi\left|\hat{s}_j^{sat}\right|^2}$$

$$\boldsymbol{a_D = a_{ng} - a_{sr} - a_{ea}}$$

*Luthcke et *al*. (1997)

2. Methods & Data processing

Reference systems in density retrieval



R_{ei} rotation Earth-fixed to ICRS :

$$\dot{\boldsymbol{r}}_{ICRS} = [\boldsymbol{PREC}][\boldsymbol{NUT}][\boldsymbol{ST}]\{[\boldsymbol{PM}]\dot{\boldsymbol{r}}_{ITRS} + \boldsymbol{\omega}_{\oplus} \times \boldsymbol{r}_{ITRS}\}$$

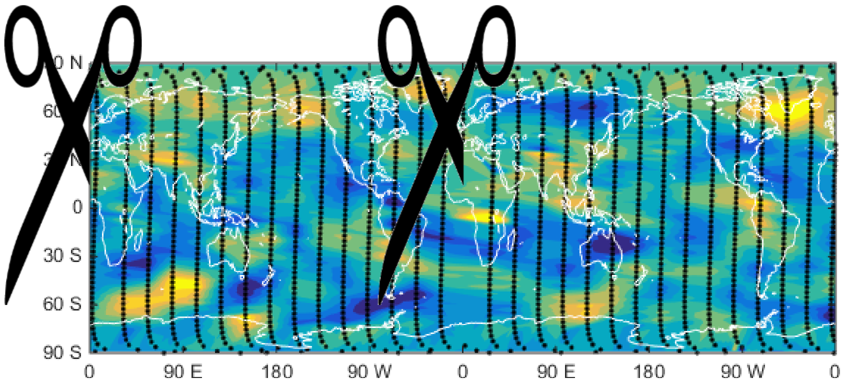
R_{ib} rotation ICRS to SBS by using star camera quaternion.
Relative velocity of the atmosphere with respect to the spacecraft

$$\mathbf{v_r} = -\dot{\mathbf{r}} + \mathbf{v_{r,c}} + \mathbf{v_{r,w}}$$

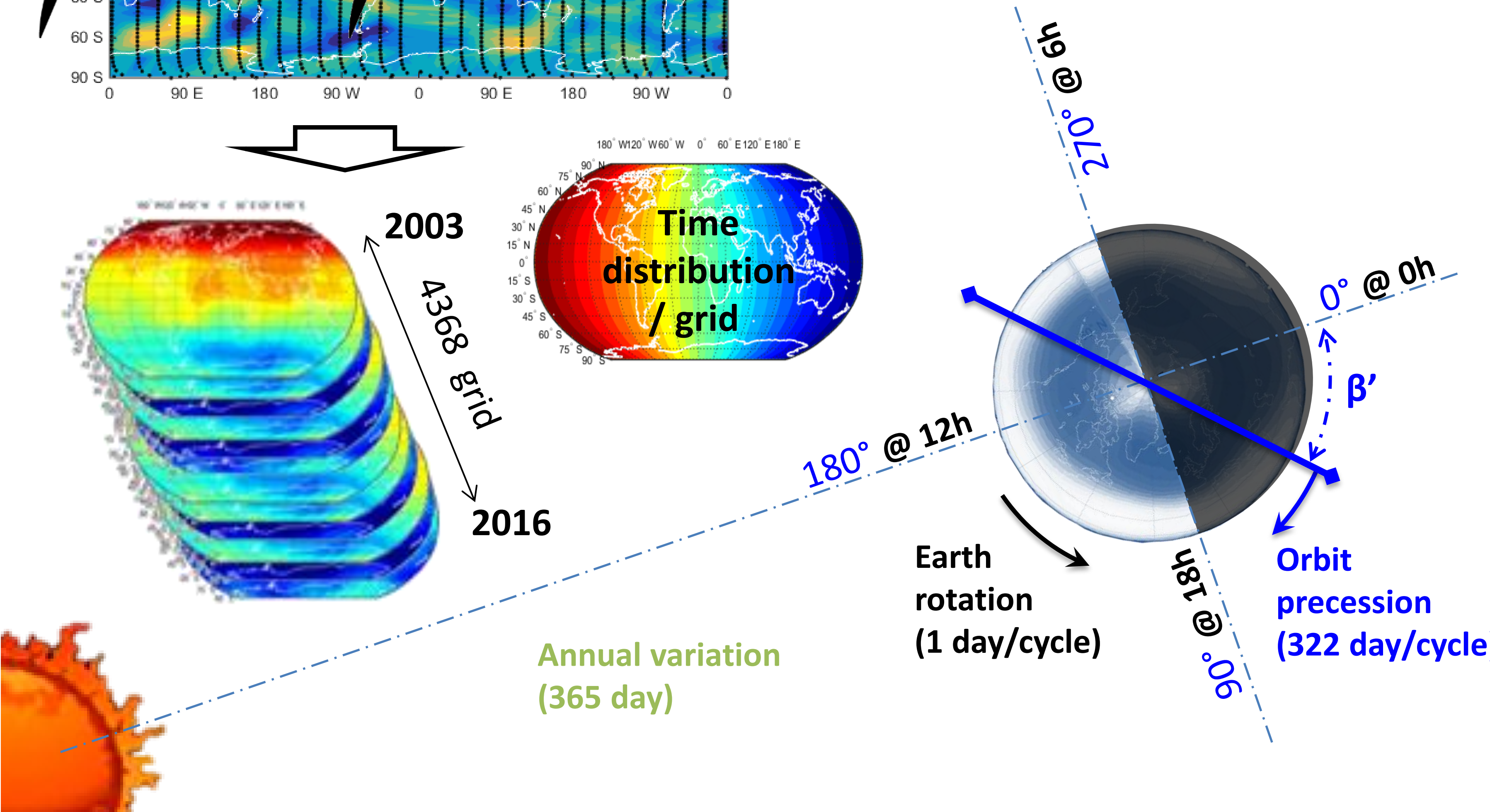
Horizontal winds from HWM07 and the co-rotating atmosphere:

$$\mathbf{v_{r,c}} = \boldsymbol{\omega}_{\oplus} \times \mathbf{r} = \mathrm{R_{ei}}[0, 0, 0.7292115 \cdot 10^{-4}\mathrm{sec}]^{\mathrm{T}} \times \mathbf{r}$$

2. Methods & Data processing



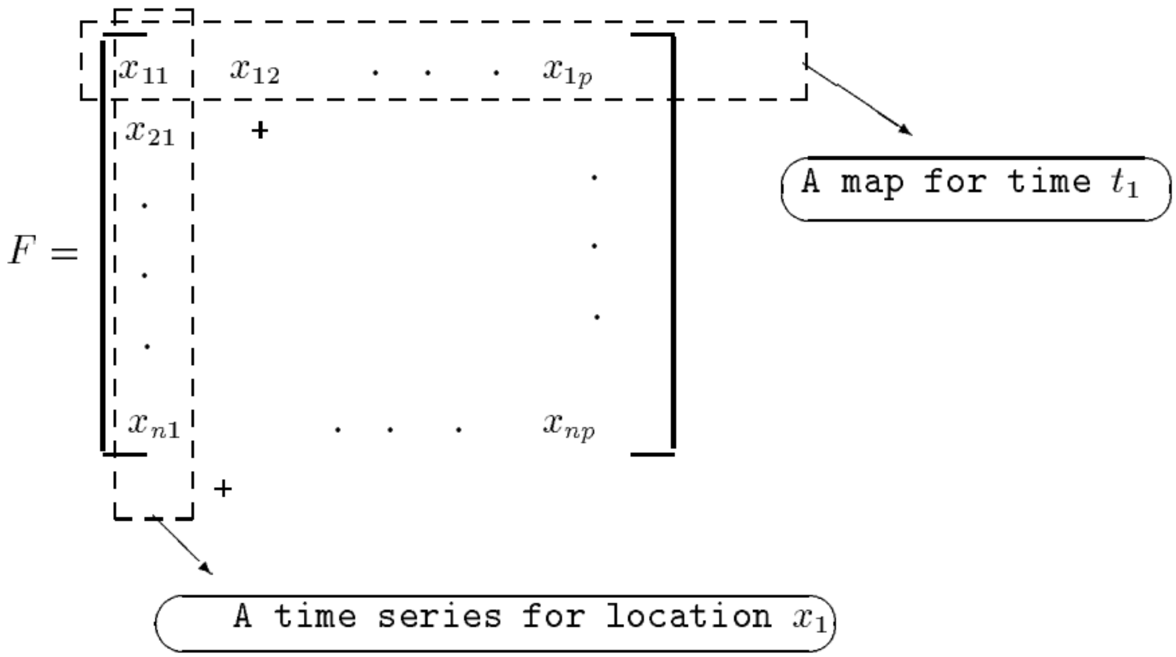
1st Density along orbit
2nd Data interpolation
3rd Grid clipping



2. Methods & Data processing

Principal Component Analysis (PCA)

4th Arrange each grid in a column.



5th Find the covariance matrix.

6th Find eigenvalues (time-coefficients) & eigenvectors (maps).

2. Methods & Data processing

Parameterization of time-expansion coefficients

7th Normalization to common flux (Muller et al. 2009):

$$\rho(P10.7 = 110) = \rho \frac{Fa(P10.7 = 110)}{Fa(P10.7)}$$

8th Fourier least-squares fitting:

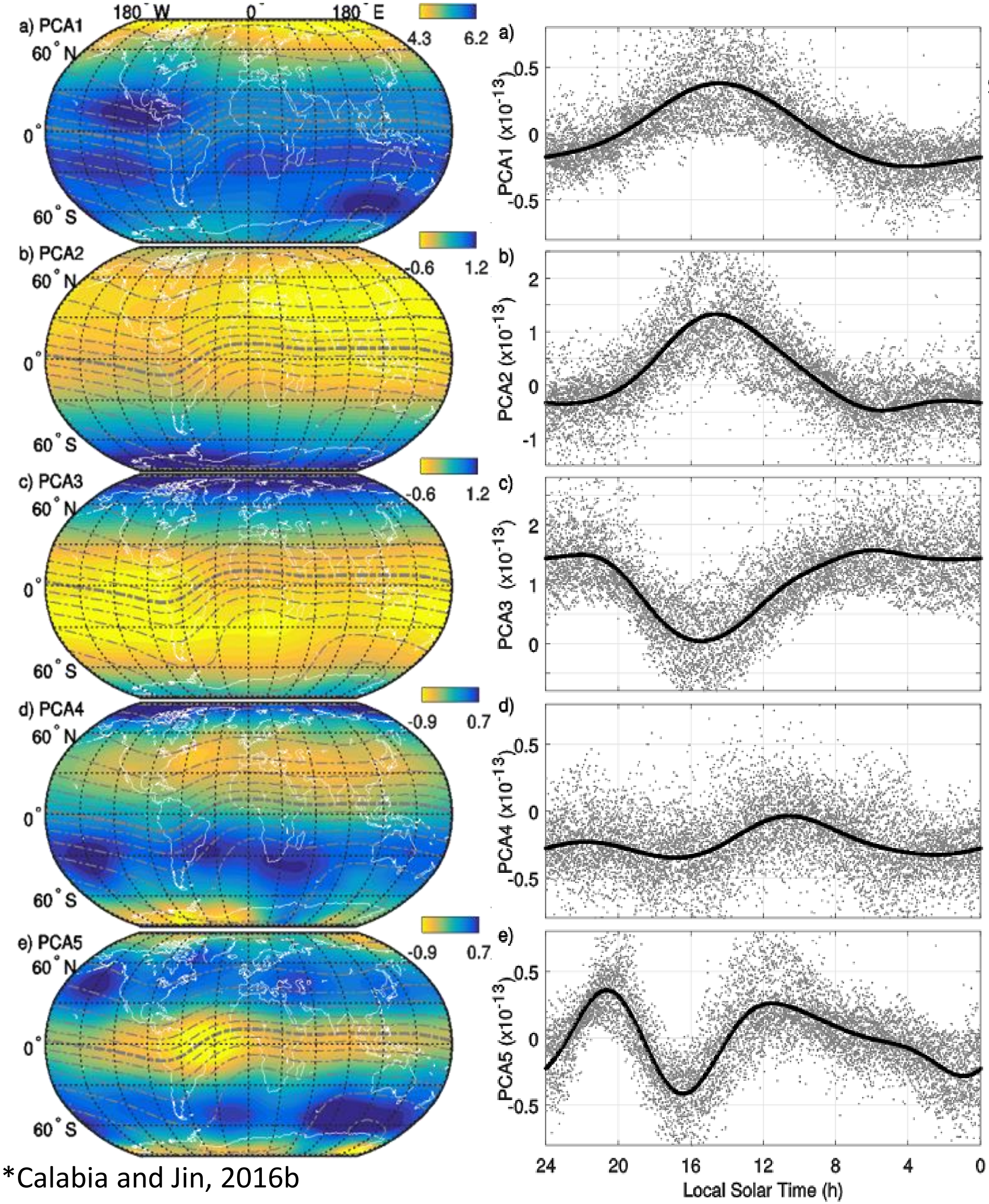
$$\sum_{i=1}^{n} \left[an \cdot cos(n \cdot \chi \cdot w) + bn \cdot sin(n \cdot \chi \cdot w) \right]$$

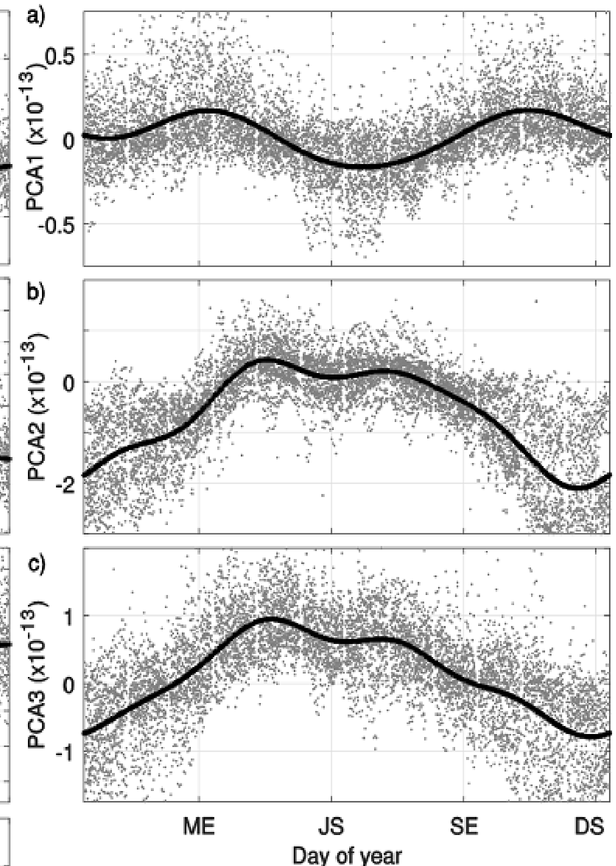
9th Polynomial fitting modulates the amplitude of the sinusoidal function computed in previous step:

$$G(\chi, P107) = 10^{-15} \cdot 10^{a} \cdot P107^{b} \cdot \left(a0 + \sum_{i=1}^{n} \left[an \cdot cos(n \cdot \chi \cdot w) + bn \cdot sin(n \cdot \chi \cdot w) \right] \right)$$

* a, b, a0, an, bn and w are the constant and amplitudes, and χ = (doy, β').

PCA parameterization



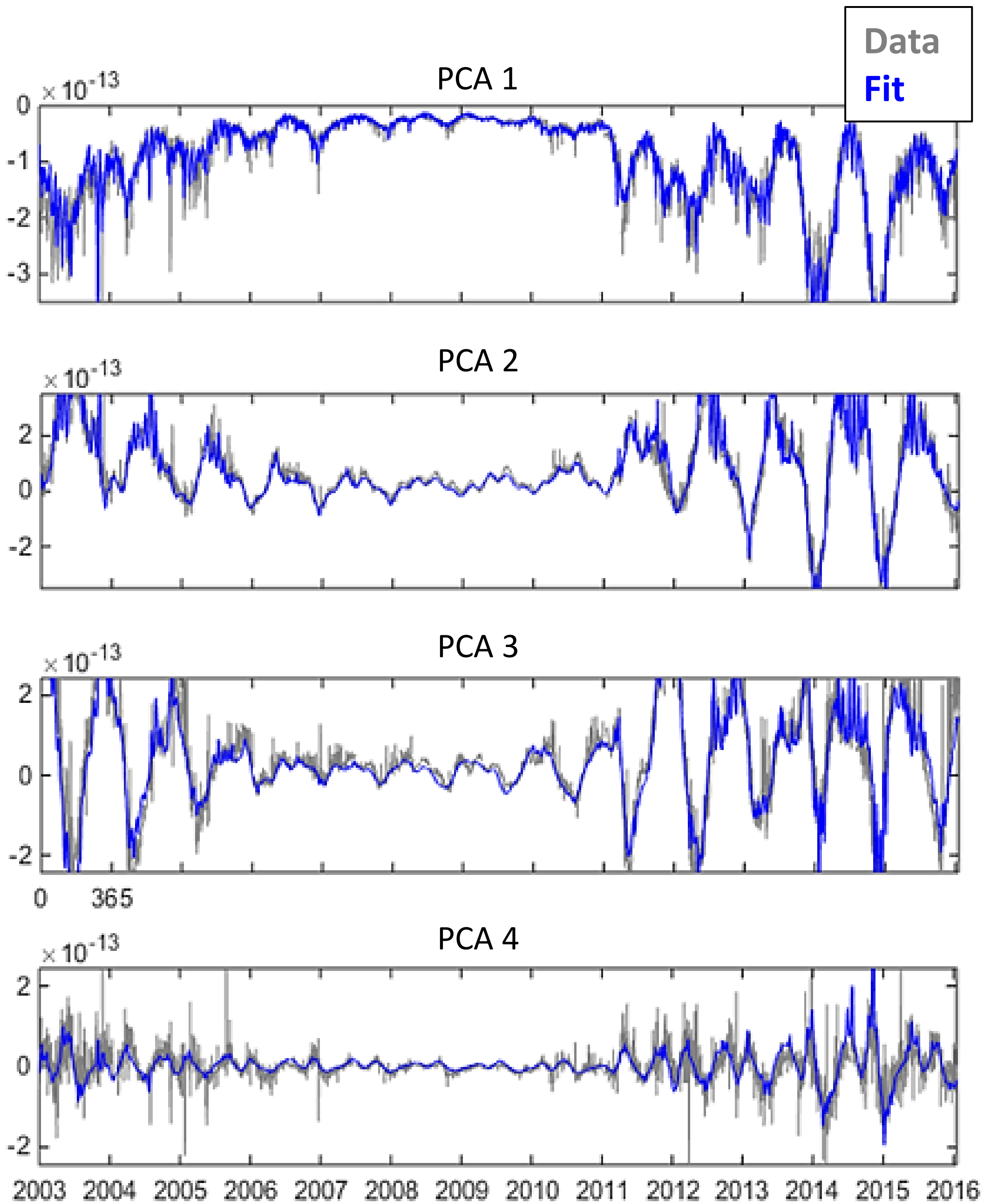


*Data normalized to P10.7=110

*Calabia and Jin, 2016b

PCA parameterization

Data vs Fit

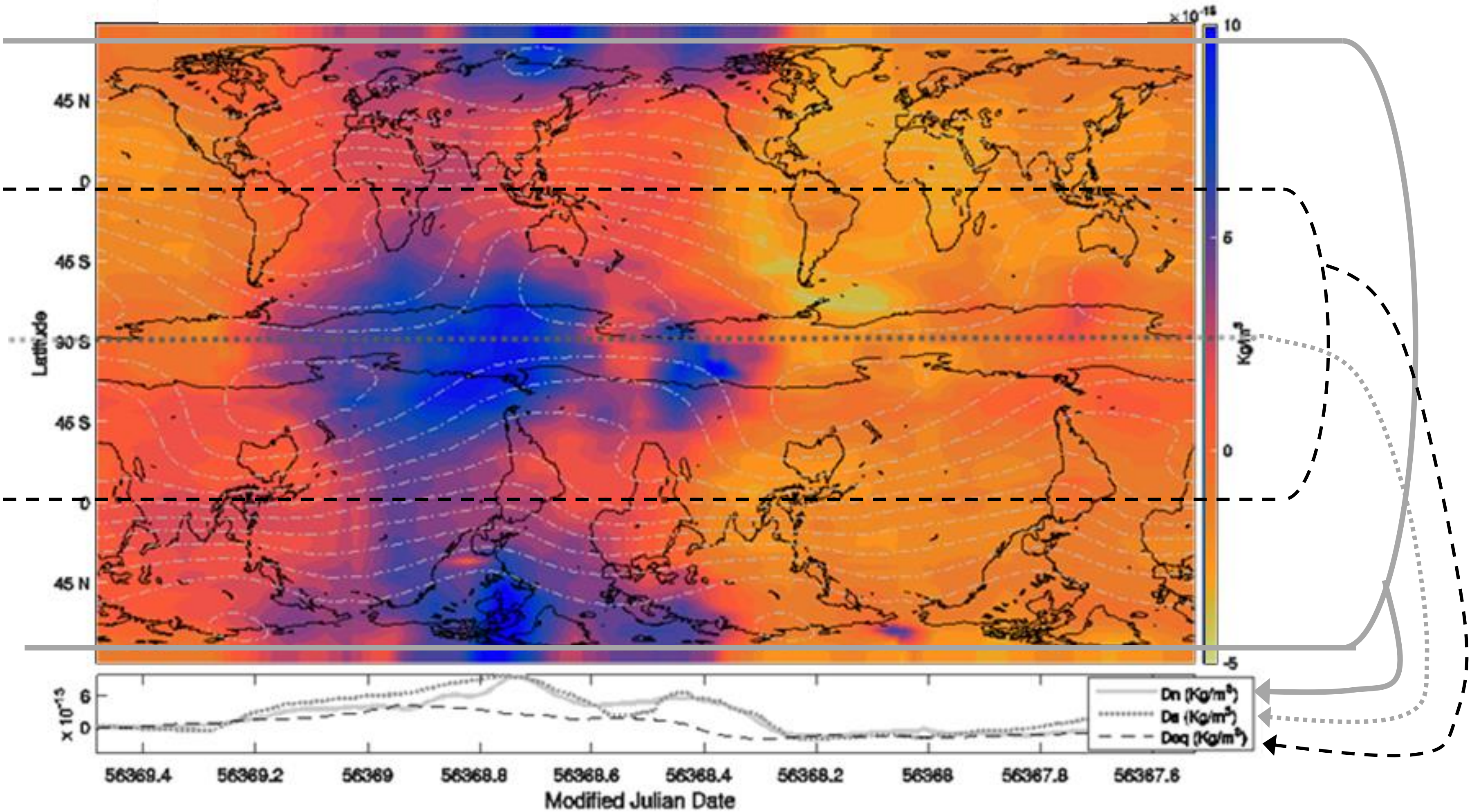


Variance explained	Data - Fit correlation
92 %	96 %
3.5%	93 %
3%	90 %
1.3 %	83 %

*Calabia and Jin, 2017

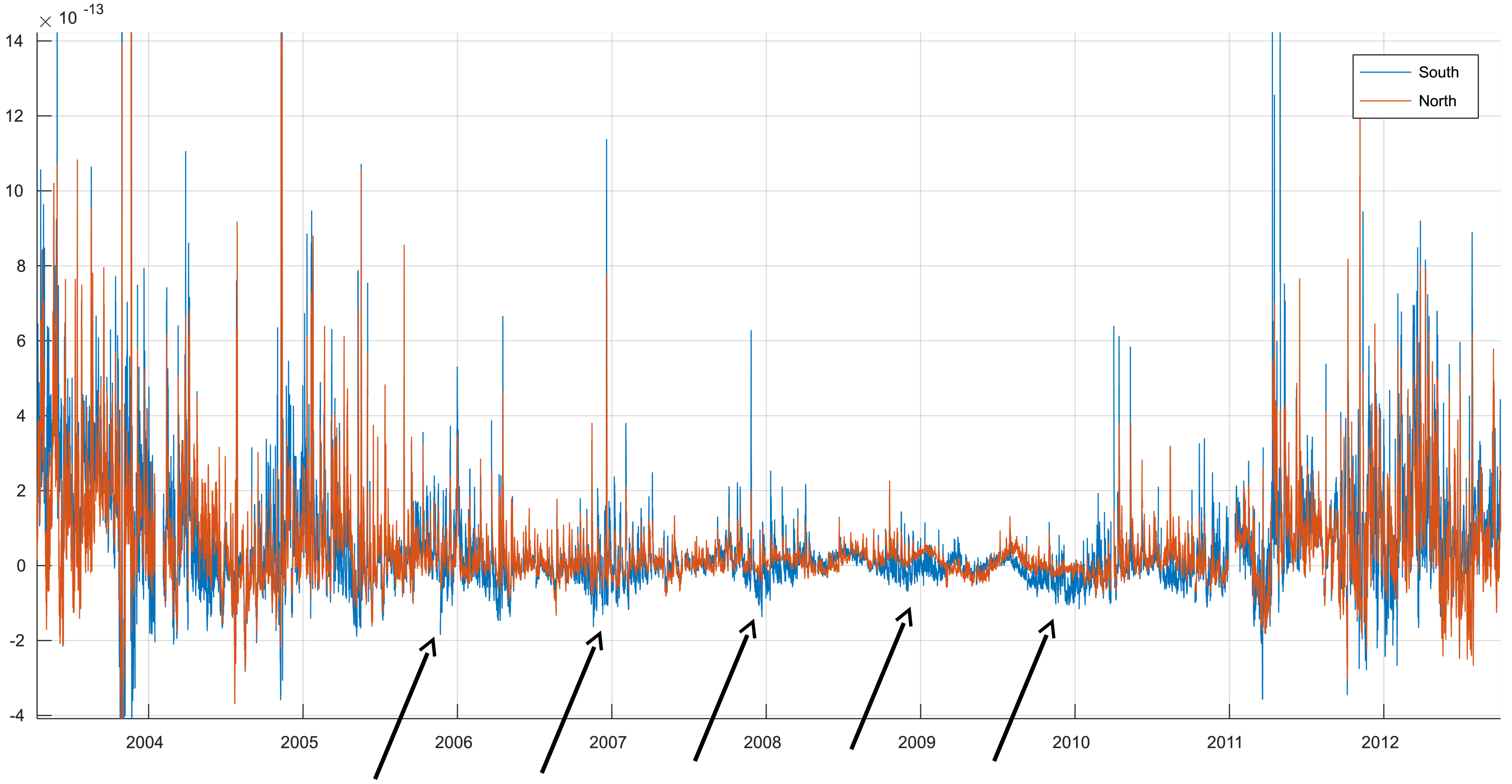
Extracting profiles of residuals

Northern, Equatorial, and Southern profiles



3. Questions & Hypothesis

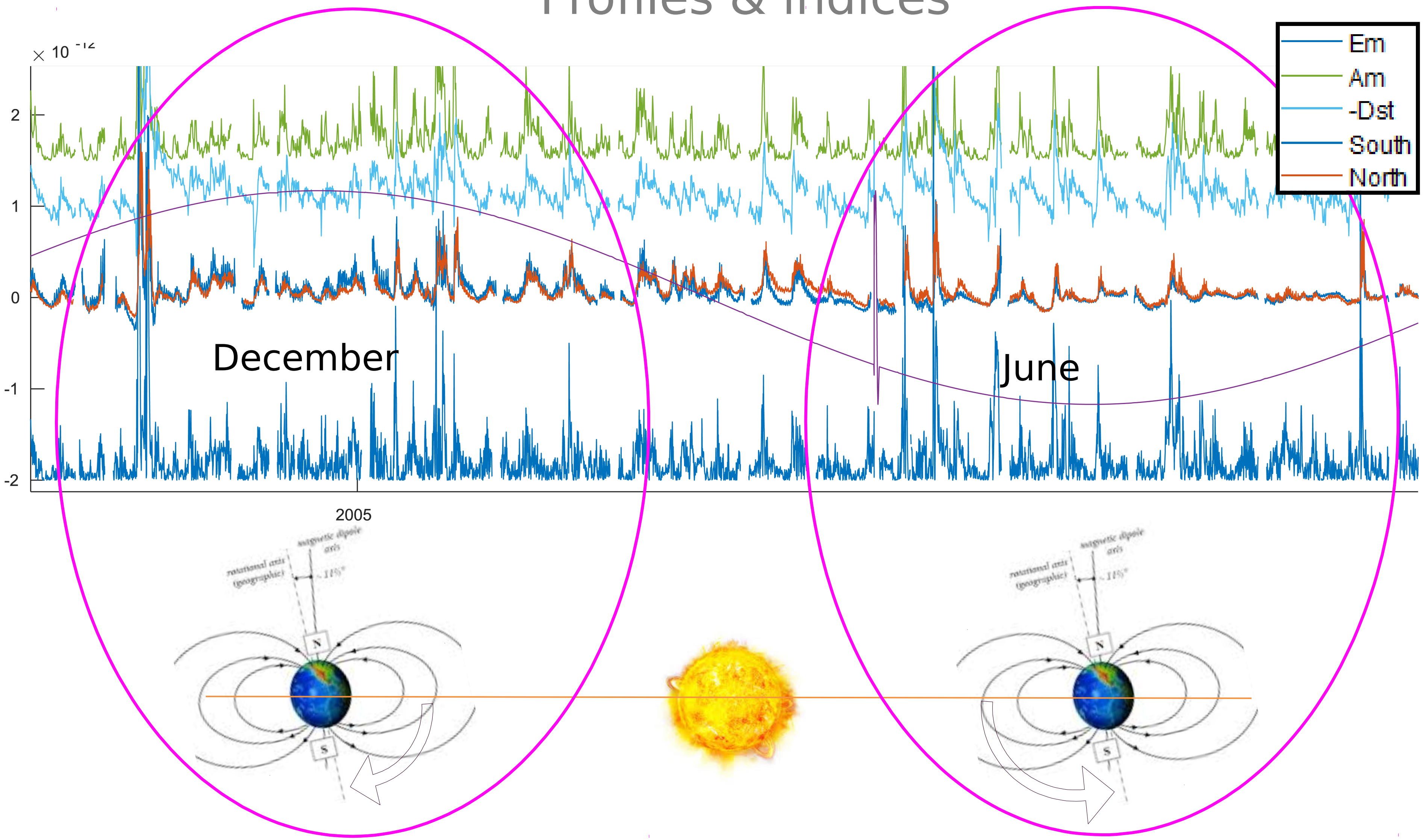
North & South profiles of density residuals (ρ_N, ρ_S)



Stronger fluctuations in December in the Southern region !

3. Questions & Hypothesis

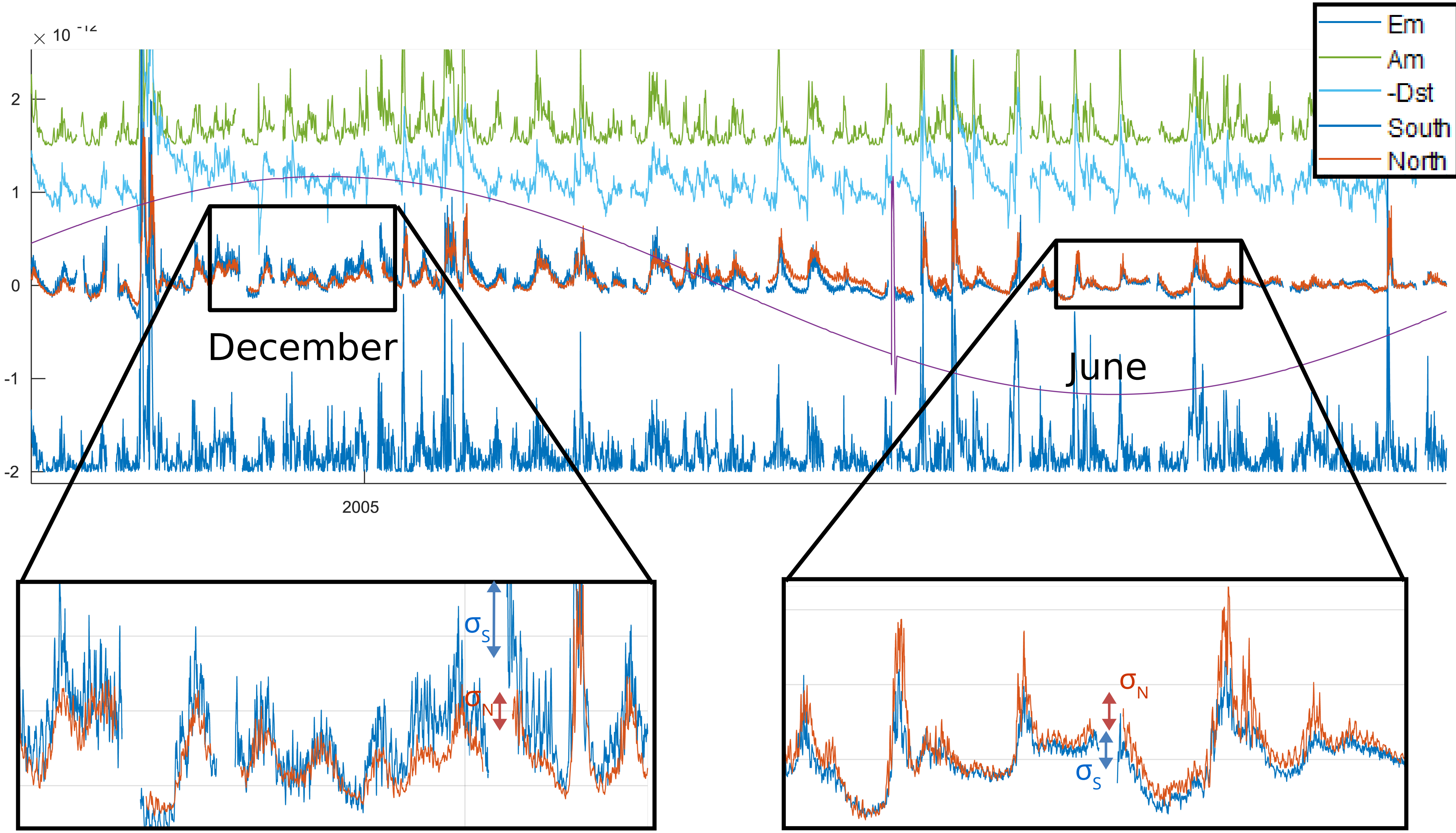
Profiles & indices



Density variations attenuate in June solstice (bigger mean magnetic dip angle) !

3. Questions & Hypothesis

Profiles & indices



Southern density fluctuations have bigger amplitude (σ) in December !

3. Questions & Hypothesis

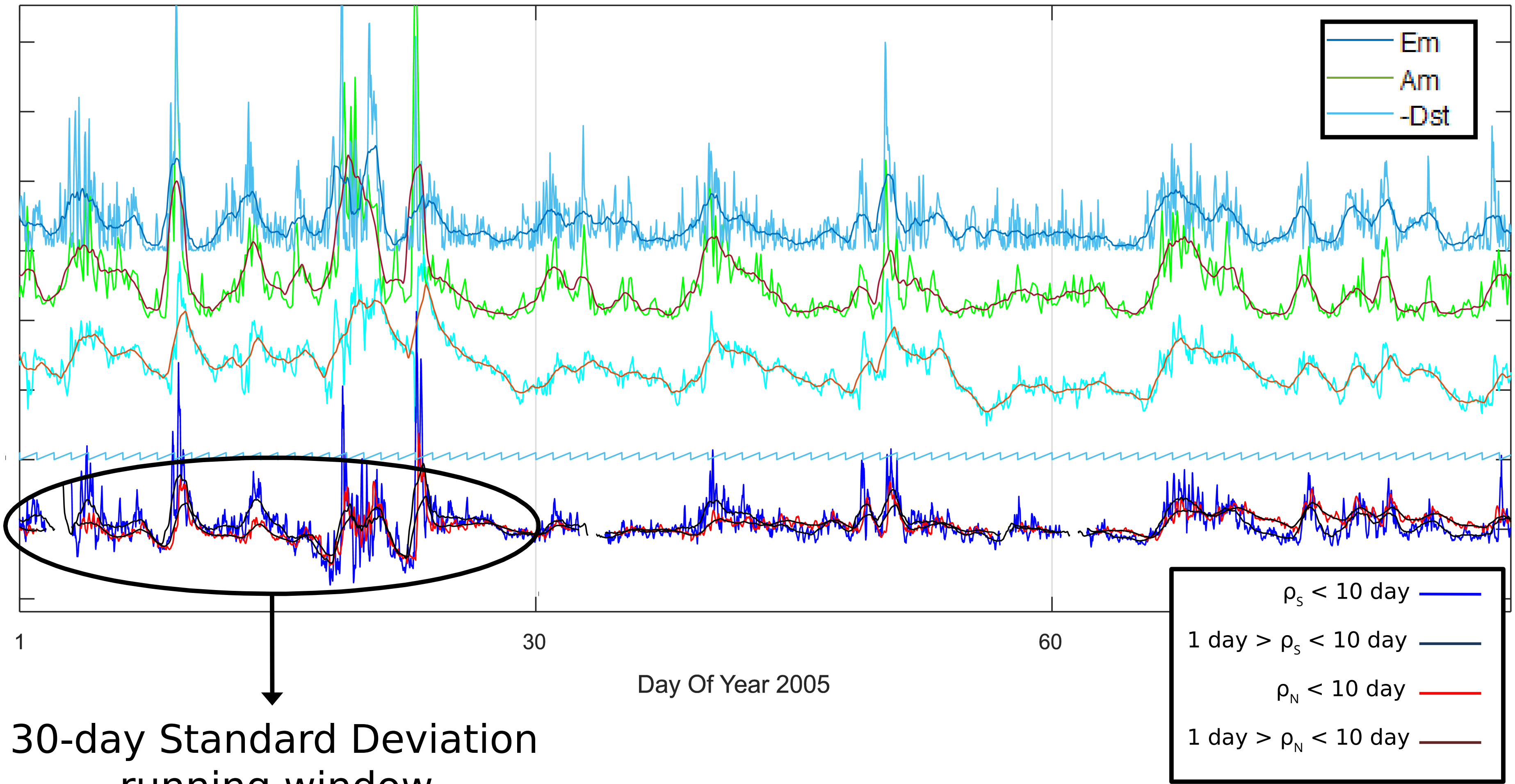
Are these variations a typical storm-time behavior?

A first-principle physical-model (e.g., TIEGCM) would reproduce these variations?

Can this behavior be modeled using the most representative proxies?

4. Analysis

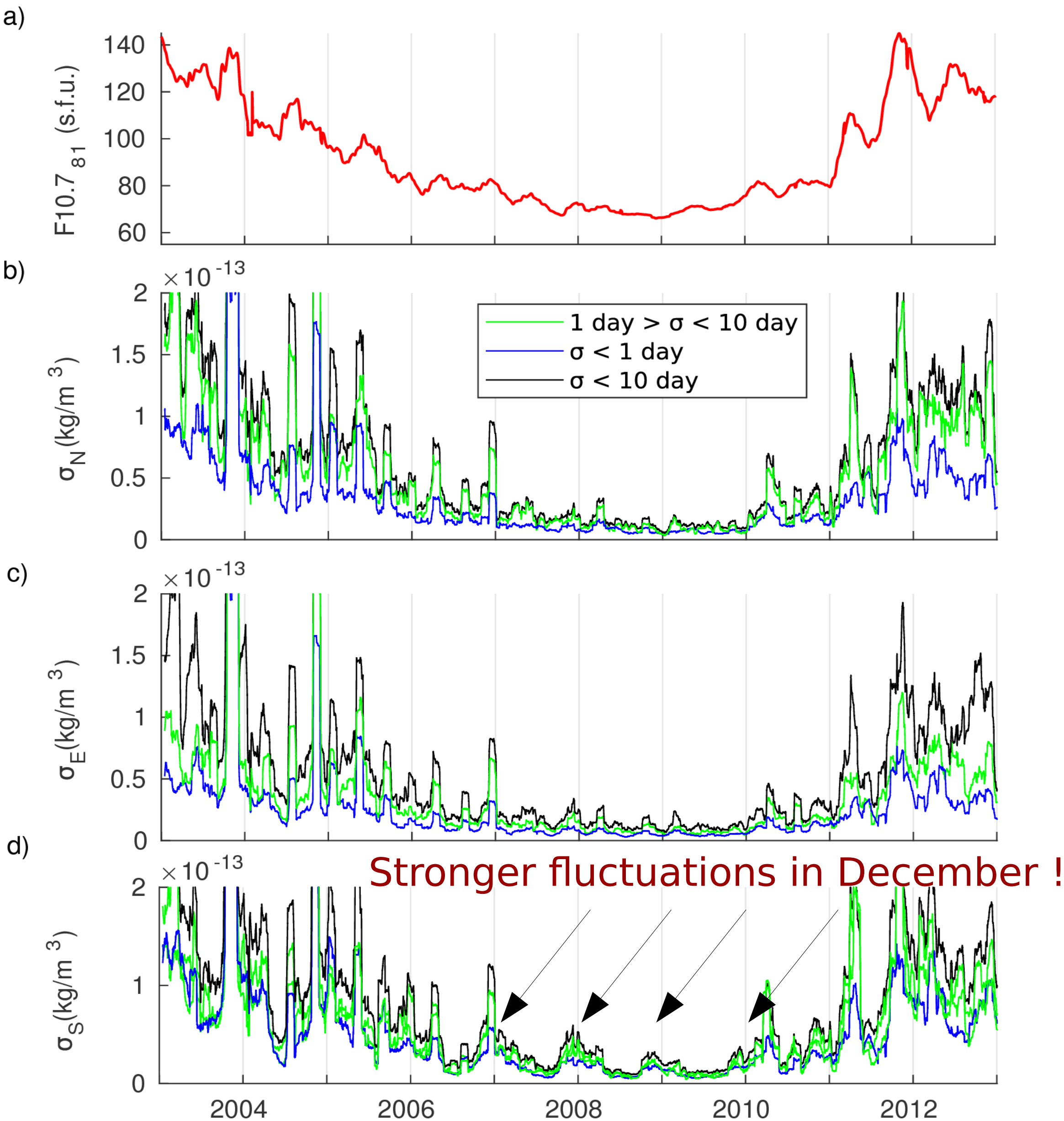
24 h & 30 day mean average running-window



30-day Standard Deviation running window.

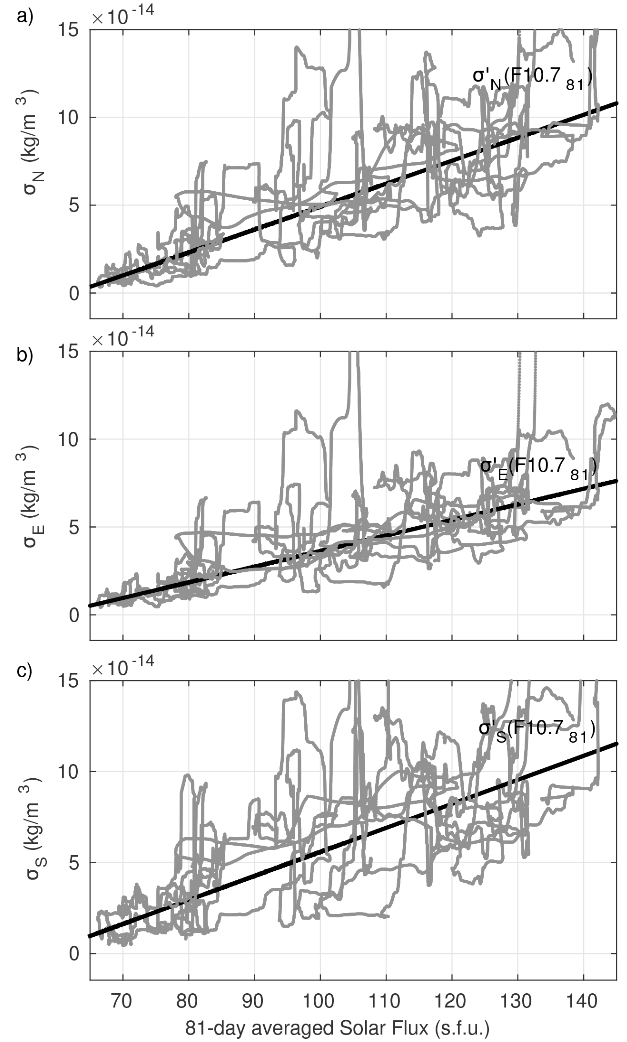
5. Results

30-day STD (σ) running-window ∝ $F10.7_{81}$



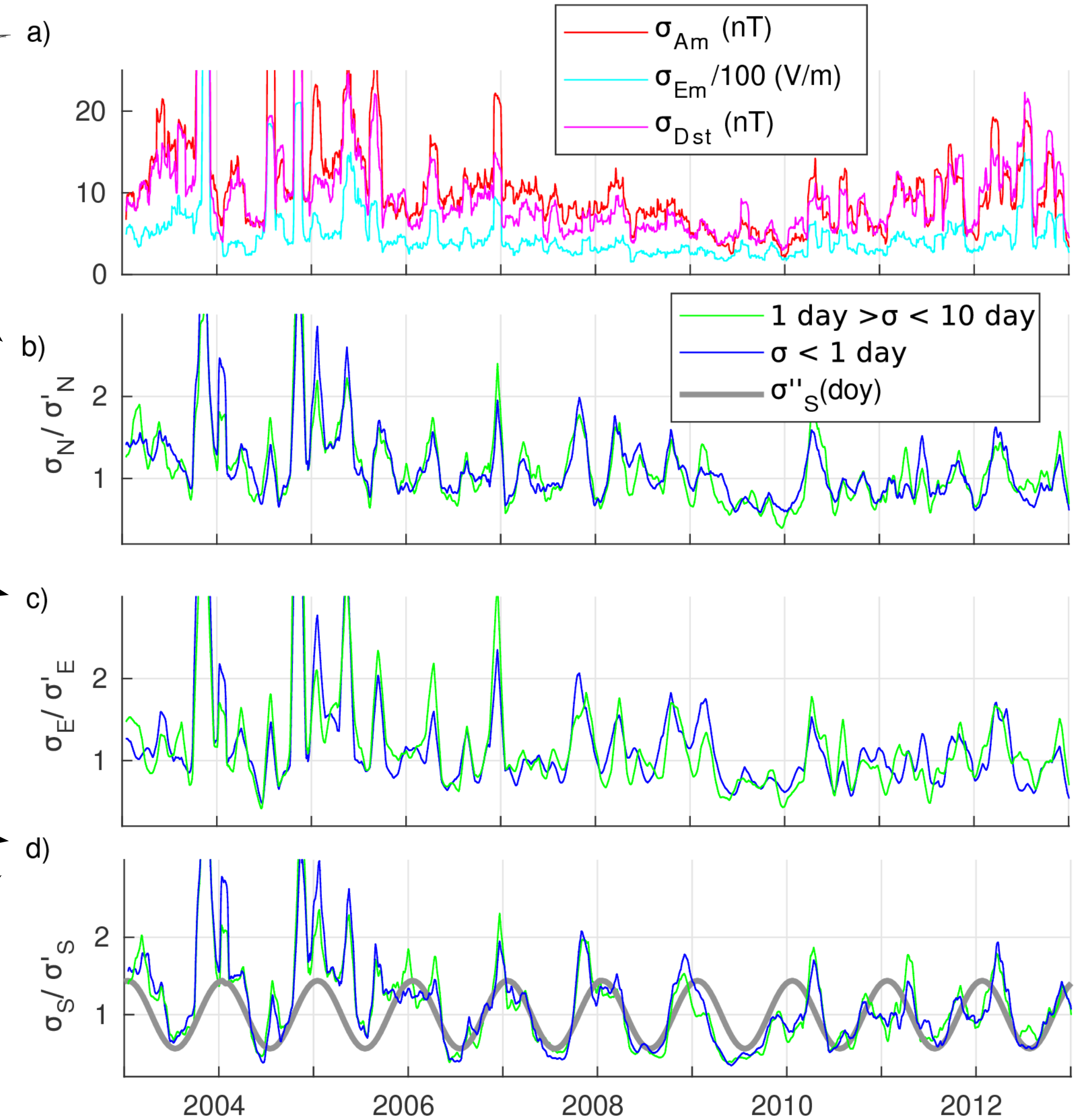
Linear Fitting:

$$\sigma'(F10.7_{81}) = p1 * F10.7_{81} + p2$$



5. Results

Agreement with proxies



Fourier Fitting:

$$\sigma_s/\sigma'_s \approx \sigma''_s(doy) = 1 + a1*\cos(doy) + b1*\sin(doy)$$

Coefficients (95% confidence):

a1 = 0.4268 (0.4256, 0.428)

B1 = 0.1016 (0.1004, 0.1027)

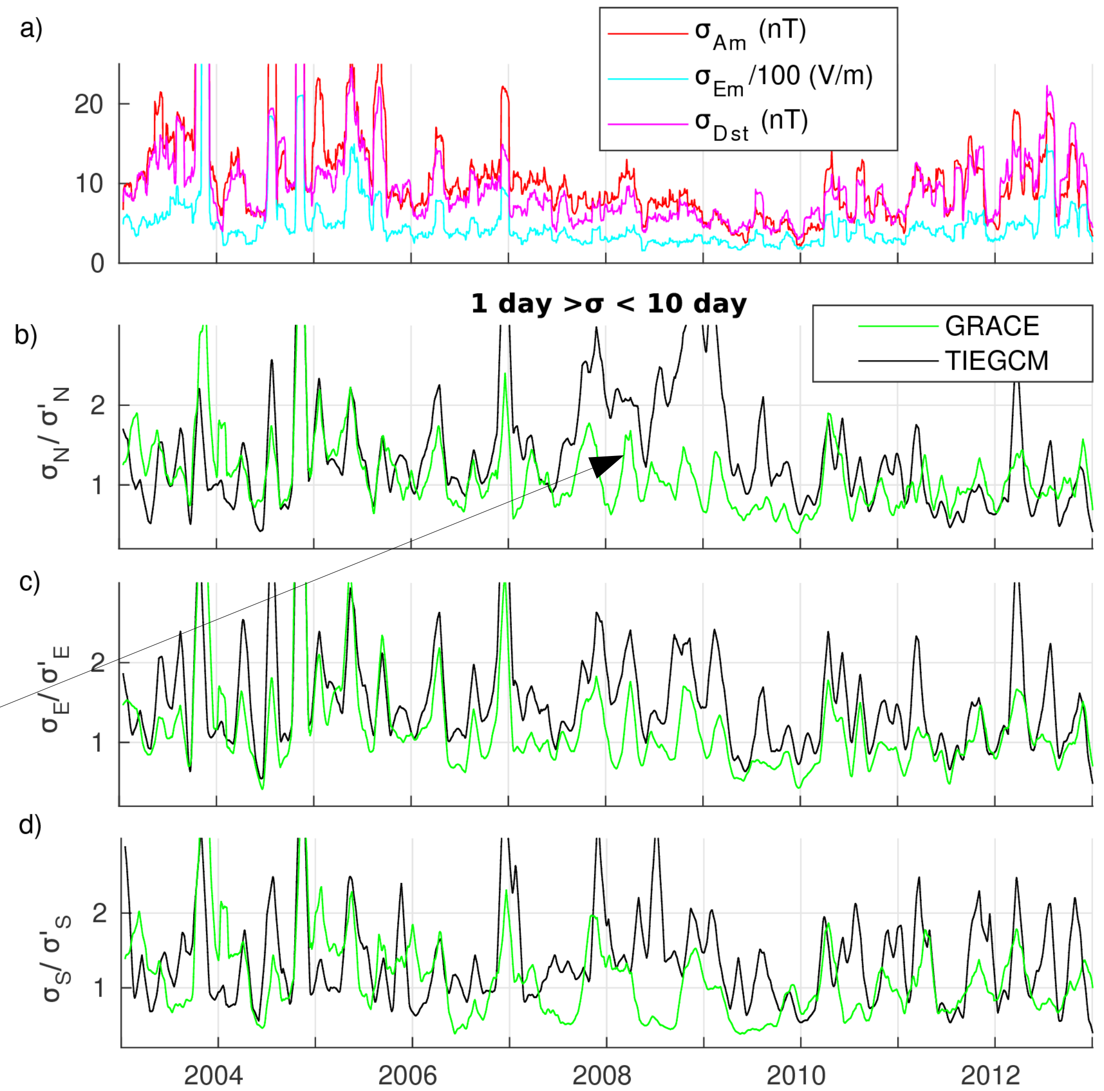
Goodness of fit:

R-square: 0.8

RMSE: 2.62e-01

5. Results

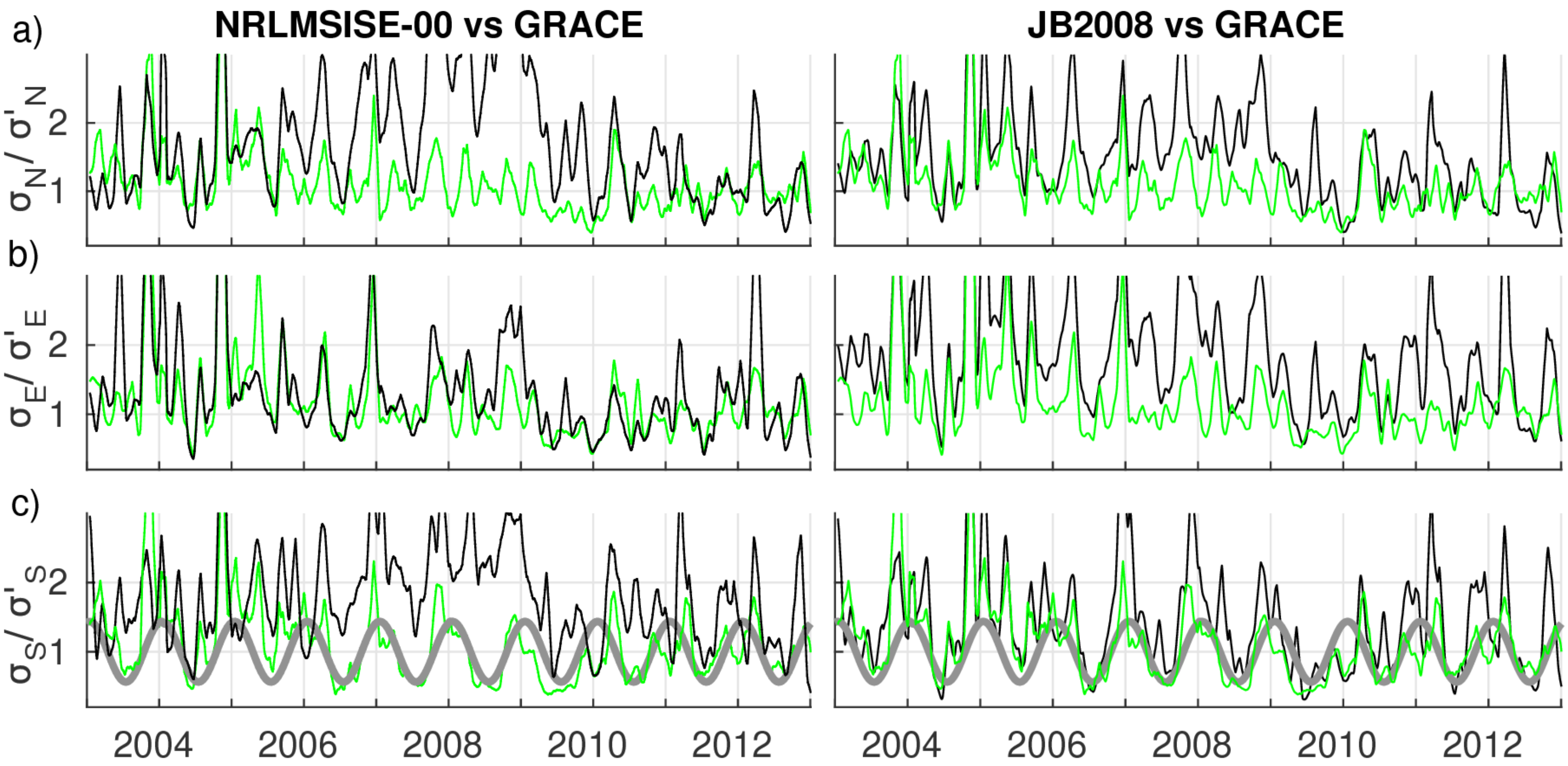
GRACE
vs
TIEGCM



TIEGCM shows bigger amplitudes in December in the Northern Polar Cap instead!

5. Results

GRACE vs Empirical models



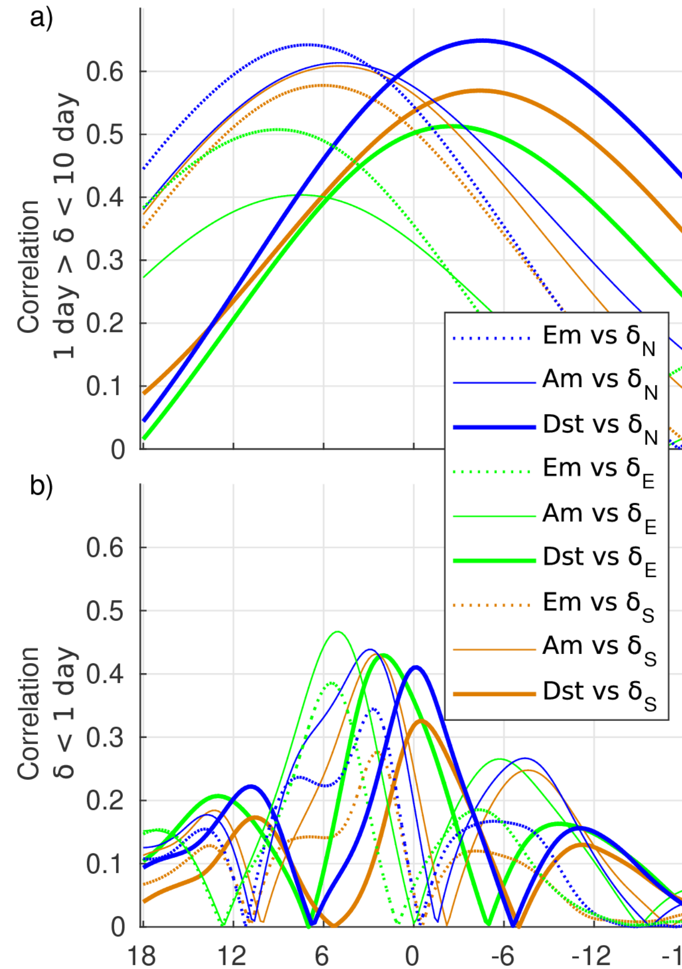
NRLMSISE00 overestimates in low solar activity al Polar Caps

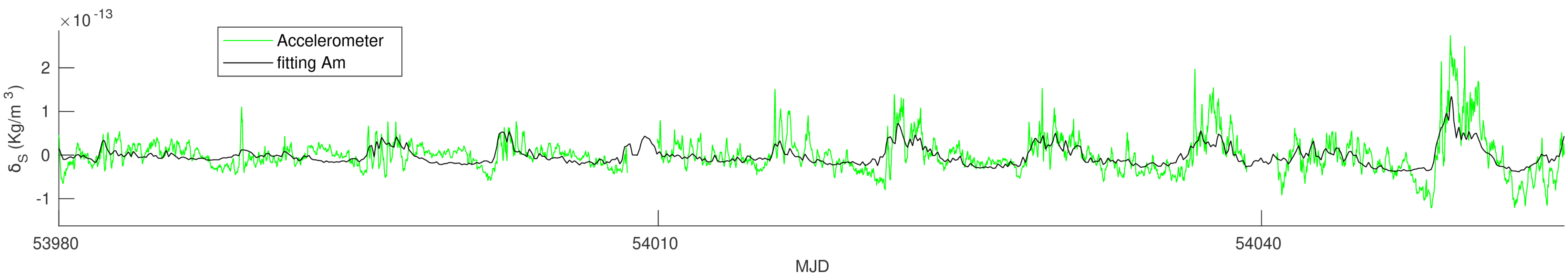
JB2008 impressive agreement in the South!

5. Results

Model in terms of indices.
Correlation vs Delay (2003-2015)

			R-square	RMSE (kg/m³)	Correlation	Delay (h)
1 day > δ < 10 day	δ_N	Dst	0.93	2.0E-14	0.65	-4.80
		Am	0.93	2.0E-14	0.61	4.60
		Em	0.91	2.1E-14	0.64	6.80
	δ_E	Dst	0.90	1.9E-14	0.51	-2.80
		Am	0.87	2.1E-14	0.36	7.40
		Em	0.87	2.1E-14	0.50	8.80
	δ_S	Dst	0.90	2.6E-14	0.56	-4.60
		Am	0.90	2.6E-14	0.62	4.80
		Em	0.90	2.7E-14	0.56	5.80
δ < 1 day	δ_N	Dst	0.89	1.7E-14	0.45	-0.40
		Am	0.89	1.6E-14	0.44	2.80
		Em	0.89	1.6E-14	0.38	2.60
	δ_E	Dst	0.91	1.3E-14	0.43	1.80
		Am	0.91	1.2E-14	0.50	4.80
		Em	0.91	1.2E-14	0.44	5.20
	δ_S	Dst	0.89	2.5E-14	0.38	-0.60
		Am	0.90	2.4E-14	0.42	2.40
		Em	0.90	2.4E-14	0.32	2.20

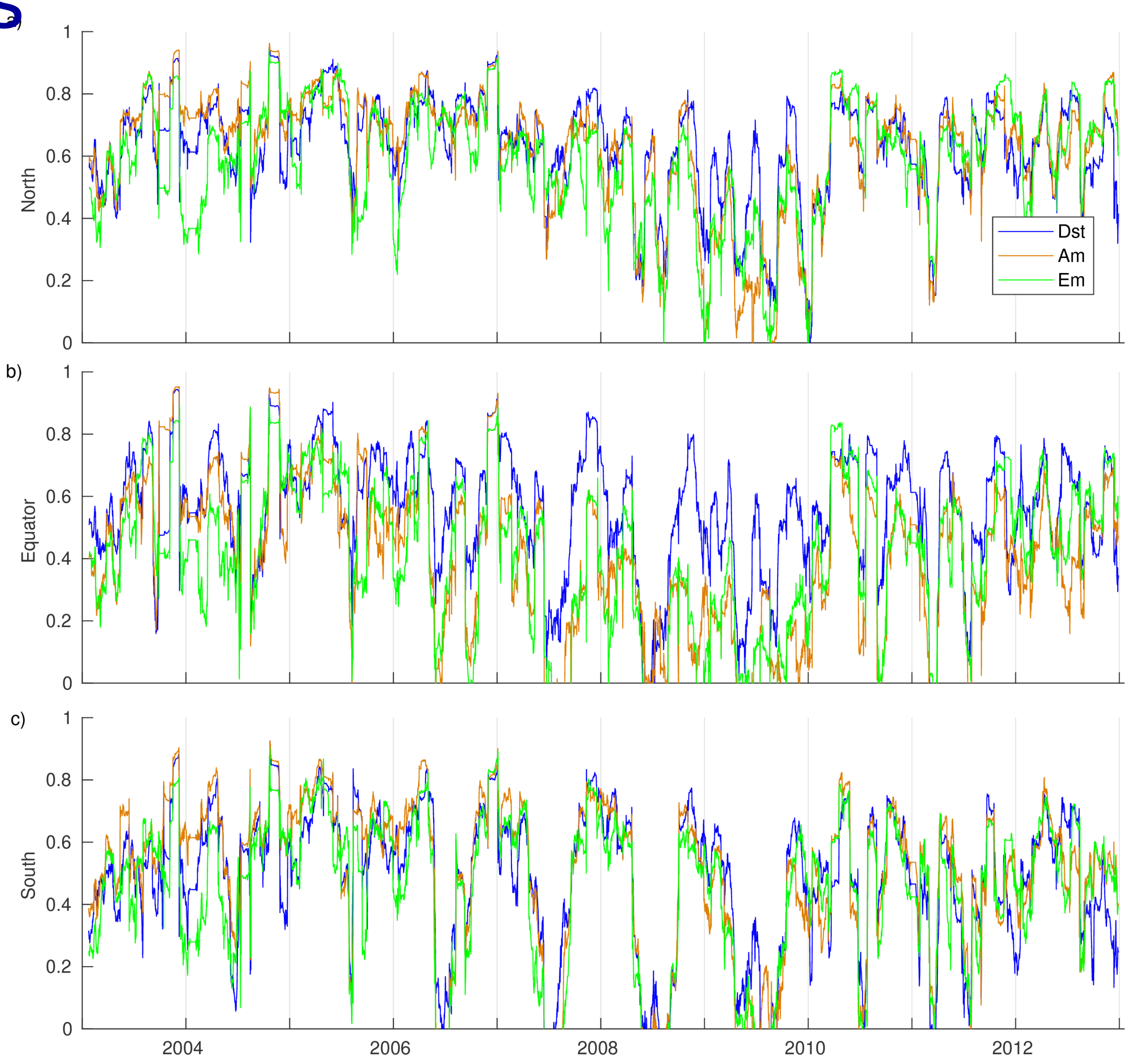




5.Results

Fitting vs GRACE

Correlation at 30-day Running window



6. Conclusions

- Neutral density variations due to geomagnetic forcing are strongly dependent on solar flux and dipole-tilt angle variations.
- Southern density variations have bigger amplitude in December, when the southern dipole is oriented to the Sun (good agreement with JB2008). TIEGCM show bigger amplitudes in December in the North instead.
- *Dst* index (variations <10 day) shows worse delay for prediction, while *Am and Em* show best suitability for prediction.

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Thank you!

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